Bohn, Brent

From: Gibbons, Catherine
Sent: Friday, December 04, 2015 7:49 PM
To: Bohn, Brent
Subject: FW: meeting update

From: Khan, Elaine@OEHHA [mailto:Elaine.Khan@oehha.ca.gov]
Sent: Friday, August 02, 2013 6:49 PM
To: Gibbons, Catherine <Gibbons.Catherine@epa.gov>
Subject: RE: meeting update

You have a good weekend too and I'll talk to you Monday!

From: Gibbons, Catherine [mailto:Gibbons.Catherine@epa.gov]
Sent: Friday, August 02, 2013 3:45 PM
To: Khan, Elaine@OEHHA
Subject: RE: meeting update

Hi Elaine!

Well that was awful, I just finished with tech support here and it still isn't fixed! Let's do try for Monday. One thing I wanted to ask you about in particular is whether you or any of your colleagues have been put out by the early times of the workshops. We had to accommodate panelists in both California and Italy, and the person in California was fine with the early time, but we've been getting some complaints. We are seeing about pushing it a bit later, but I'm not sure we will be able to.

We can talk about it on Monday. I'll try calling you when I get a free minute later in the afternoon. Thank you!

Have a good weekend,

Catherine

From: Khan, Elaine@OEHHA [mailto:Elaine.Khan@oehha.ca.gov]
Sent: Friday, August 02, 2013 3:57 PM
To: Gibbons, Catherine
Subject: RE: meeting update

I have a meeting 1:30-2:00 my time, but I'm free otherwise (here 'til about 5 pm PDT). If we miss each other today, let's try for Monday or whenever you have time next week, ok? Thanks!

Elaine

From: Gibbons, Catherine [mailto:Gibbons.Catherine@epa.gov]
Sent: Friday, August 02, 2013 12:41 PM
To: Khan, Elaine@OEHHA
Subject: RE: meeting update

Hi Elaine!

Sorry for the delay, I've been having some computer issues today that are very distracting. How late are you going to be in today? I may be able to talk in another hour or so.

Thanks!

Catherine

From: Khan, Elaine@OEHHA [mailto:Elaine.Khan@oehha.ca.gov]
Sent: Friday, August 02, 2013 1:56 PM
To: Gibbons, Catherine
Subject: meeting update

Hi, Catherine.

Glad to see the Cr6 workshop has been announced – I'm already registered! I also wanted to touch base with you about how our meeting went last month. Let me know when's a good time to call and we can chat. Thanks!

Elaine

Bohn, Brent

From: Gibbons, Catherine
Sent: Friday, December 04, 2015 7:49 PM
To: Bohn, Brent
Subject: FW: papers on de-differentiation and autophagy

From: Gibbons, Catherine
Sent: Monday, August 05, 2013 5:27 PM
To: Elaine.Khan@oehha.ca.gov
Subject: RE: papers on de-differentiation and autophagy

Hi Elaine, wow, thank you, I'd actually much rather have these references to review now, I'm in no hurry for the other one to come out! Plenty of work to do! This was really nice of you, I am anxious to get back into this, I'm getting really tired of reading about reduction kinetics.

Thanks so much!

Catherine

From: Khan, Elaine@OEHHA [mailto:Elaine.Khan@oehha.ca.gov]
Sent: Monday, August 05, 2013 3:05 PM
To: Gibbons, Catherine
Subject: papers on de-differentiation and autophagy

Hi, Catherine.

It was great catching up with you on our favorite topic this morning! Here are a couple of the papers I mentioned. I think I was mistaken about the third paper being published – I don't see it on the journal's website and I'm not sure if it's a good idea for me to pass it along at this time (better safe than sorry) although I'm sure if you emailed them, they would be happy to send it.

Don't hesitate to call or email if there's anything else you'd like to discuss. Hope to see you in September!

Elaine

Bohn, Brent

From: Gibbons, Catherine
Sent: Friday, December 04, 2015 7:48 PM
To: Bohn, Brent
Subject: FW: CA Cr6 MCL

From: Khan, Elaine@OEHHA [mailto:Elaine.Khan@oehha.ca.gov]
Sent: Thursday, August 22, 2013 4:22 PM
To: Sasso, Alan <Sasso.Alan@epa.gov>; Gibbons, Catherine <Gibbons.Catherine@epa.gov>
Subject: RE: CA Cr6 MCL

Thanks, Alan. I'm registered and looking forward to the workshop!

From: Sasso, Alan [mailto:Sasso.Alan@epa.gov]
Sent: Thursday, August 22, 2013 12:06 PM
To: Khan, Elaine@OEHHA; Gibbons, Catherine
Subject: RE: CA Cr6 MCL

Thanks Elaine,

Also, we've recently posted new information regarding the hexavalent chromium webinar to our website:

http://www.epa.gov/iris/irisworkshops/cr6/index.htm

The panelist names, and the white paper are now public.

Hope you can call in, despite the early time! We have a panelist in Italy, which is why the time is so early.

Be sure to register if you haven't already. Let us know if you have any questions or need any clarifications on the new information posted.

Thanks again,

-Alan

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Office of Research and Development
National Center for Environmental Assessment
U.S. Environmental Protection Agency
(703)-347-0179

From: Khan, Elaine@OEHHA [mailto:Elaine.Khan@oehha.ca.gov]
Sent: Thursday, August 22, 2013 2:53 PM

To: Gibbons, Catherine
Cc: Sasso, Alan
Subject: CA Cr6 MCL

Hi, Catherine and Alan.

Fyi, California is releasing a proposed Cr6 MCL (10 ppb) for public comment.
http://www.cdph.ca.gov/certlic/drinkingwater/Pages/Chromium6.aspx

Elaine

Bohn, Brent

From: Gibbons, Catherine
Sent: Friday, December 04, 2015 7:48 PM
To: Bohn, Brent
Subject: FW: Cr6 Risk Assessment Paper
Attachments: Thompson-2013JApplTox.pdf

From: Khan, Elaine@OEHHA [mailto:Elaine.Khan@oehha.ca.gov]
Sent: Wednesday, August 14, 2013 1:32 PM
To: Gibbons, Catherine <Gibbons.Catherine@epa.gov>
Subject: Cr6 Risk Assessment Paper

Hi, Catherine.

The Cr6 risk assessment paper was published online last night. Enjoy!

Elaine

Research Article

Journal of Applied Toxicology

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(wileyonlinelibrary.com) DOI 10.1002/jat.2907

A chronic oral reference dose for hexavalent chromium-induced intestinal cancer†

Chad M. Thompson[a]*, Christopher R. Kirman[b], Deborah M. Proctor[c], Laurie C. Haws[d], Mina Suh[c], Sean M. Hays[e], J. Gregory Hixon[d] and Mark A. Harris[a]

ABSTRACT: High concentrations of hexavalent chromium [Cr(VI)] in drinking water induce villous cytotoxicity and compensatory crypt hyperplasia in the small intestines of mice (but not rats). Lifetime exposure to such cytotoxic concentrations increases intestinal neoplasms in mice, suggesting that the mode of action for Cr(VI)-induced intestinal tumors involves chronic wounding and compensatory cell proliferation of the intestine. Therefore, we developed a chronic oral reference dose (RfD) designed to be protective of intestinal damage and thus intestinal cancer. A physiologically based pharmacokinetic model for chromium in mice was used to estimate the amount of Cr(VI) entering each intestinal tissue section (duodenum, jejunum and ileum) from the lumen per day (normalized to intestinal tissue weight). These internal dose metrics, together with corresponding incidences for diffuse hyperplasia, were used to derive points of departure using benchmark dose modeling and constrained nonlinear regression. Both modeling techniques resulted in similar points of departure, which were subsequently converted to human equivalent doses using a human physiologically based pharmacokinetic model. Applying appropriate uncertainty factors, an RfD of 0.006 mg kg^{-1} day^{-1} was derived for diffuse hyperplasia—an effect that precedes tumor formation. This RfD is protective of both noncancer and cancer effects in the small intestine and corresponds to a safe drinking water equivalent level of 210 μg l^{-1}. This concentration is higher than the current federal maximum contaminant level for total Cr (100 μg l^{-1}) and well above levels of Cr(VI) in US drinking water supplies (typically ≤5 μg l^{-1}). © 2013 The Authors. *Journal of Applied Toxicology* published by John Wiley & Sons, Ltd.

Supporting Information may be found in the online version of this article.

Keywords: risk assessment; hexavalent chromium Cr(VI); mode of action; benchmark dose (BMD) modeling; constrained nonlinear regression; cancer reference dose (RfD); intestinal cancer

Introduction

Exposure to hexavalent chromium [Cr(VI)] has long been recognized to increase the risk of lung cancer among workers in certain industries (IARC, 1990), as well as in rodents via inhalation or intratracheal instillation (Glaser *et al.*, 1986; Steinhoff *et al.*, 1986). Owing to protective reductive mechanisms, ingestion of Cr(VI) was thought to pose relatively little cancer risk (De Flora *et al.*, 1987; De Flora *et al.*, 1997; Febel *et al.*, 2001; Proctor *et al.*, 2002). In fact, Cr(VI) has not been shown to cause a significantly increased cancer risk in the alimentary canal of exposed workers (Gatto *et al.*, 2010). However, a recent 2-year cancer bioassay indicated that chronic exposure to Cr(VI), administered as sodium dichromate dihydrate, caused a dose-dependent increase in intestinal damage and intestinal tumor formation in B6C3F1 mice, but not F344 rats (NTP, 2008b). Subchronic bioassays indicated increased intestinal damage in mice after 90 days of exposure, but without evidence of preneoplastic lesions (NTP, 2007; Thompson *et al.*, 2011b). It is well known that chemicals that cause cytotoxicity and subsequently induce cell proliferation in shorter-term assays are often carcinogenic in longer-term bioassays (Ames *et al.*, 1993; Boobis *et al.*, 2009; Cohen, 2010; Gaylor, 2005). Thus, the disparate outcomes observed in mice and rats suggested that the intestinal tumors observed in mice

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were the result of chronic mucosal injury with compensatory regenerative hyperplasia.

To investigate the mode of action (MOA) underlying intestinal tumors in mice, a series of studies were conducted to collect biochemical, histological and pharmacokinetic data in the rodent small intestine (see section on "Mode of action for intestinal neoplasms"). Collectively, these studies indicate that Cr(VI) induced early and prolonged (lifetime) intestinal damage and crypt hyperplasia in mice. Despite the increase in crypt hyperplasia, exposure to Cr(VI) for up to 90 days did not induce cytogenetic damage in duodenal crypts cells or increase K-*ras* mutant frequency in duodenal tissues at carcinogenic concentrations (O'Brien *et al.*, 2013). The weight of evidence from the aforementioned studies supports a nonmutagenic MOA based on chronic intestinal wounding of nonproliferative villous tissue, which results in compensatory regenerative crypt hyperplasia and, ultimately, intestinal carcinogenesis (Thompson *et al.*, 2013). Therefore, an oral reference dose (RfD) that is protective of diffuse hyperplasia would also be protective of Cr (VI)-induced intestinal cancer. An RfD based on intestinal irritation has previously deemed protective for other small intestine (SI) carcinogens (Gordon, 2007; US EPA, 2004).

The purpose of this article is to describe the derivation of an RfD that is protective of both cancer and noncancer effects of Cr(VI) in the SI. Dose–response data collected by the National Toxicology Program (NTP) indicate a response gradient for mouse SI hyperplasia and tumor formation, with responses being greatest in the duodenum, moderate in the jejunum, and absent in the ileum (Fig. 1; (NTP, 2008b)). Target tissue chromium concentration data collected from mice indicate that total chromium concentrations in the SI exhibit a strong concentration-dependent gradient that parallels the observed tissue responses in the NTP bioassay, with chromium concentrations being highest in the duodenum, moderate in the jejunum and relatively low in the ileum (Kirman *et al.*, 2012; Thompson *et al.*, 2011b). A rodent physiologically based pharmacokinetic (PBPK) model was used to estimate target tissue doses for Cr(VI) corresponding to applied doses in the NTP 2-year animal bioassay. Because tissue response data were collected from each of the SI sections (duodenum, jejunum, ileum) of male and female mice from four different treatment groups, a robust dose–response data set was generated with as many as 24 data points (four dose groups, two sexes, three intestinal segments per animal), each representing approximately 50 observations. Benchmark dose (BMD) modeling and constrained nonlinear regression (CNR) techniques were used to derive points of departure (PODs) that were subsequently converted to human equivalent doses using a human PBPK model (Kirman *et al.*, 2013). Applying standard uncertainty factors allowed for the derivation of a chronic RfD and drinking water equivalent level. This Cr(VI) risk assessment is technically and scientifically more refined than previous assessments, because it: (1) uses MOA information to identify critical precursor endpoints for dose–response analysis; (2) uses MOA information to inform appropriate low-dose extrapolation methods; (3) employs rodent and human PBPK models to quantify target tissue dose and extrapolate between species and across dose levels; and (4) applies multiple quantitative dose–response modeling techniques. Further, the methods and approaches used in this assessment are consistent with US EPA guidance on best risk assessment practices (US EPA, 2005, 2006, 2011, 2012).

Methods

Data selection

For dose–response modeling of diffuse hyperplasia and tumor formation, male and female data were combined because visual examination (see Fig. 1; NTP, 2008b) and statistical analysis revealed no evidence of sex differences in response to Cr(VI). Specifically, logistic regression was conducted using each response variable as the dependent variable, and dose, sex, and the dose × sex interaction as independent variables. The main effect of sex and the dose × sex interaction effect were assessed for each of the six combinations of response (adenoma/carcinoma or hyperplasia) and segment (duodenum, jejunum or ileum). The results for each effect were then combined into a composite test. Across the six combinations there was no main effect of sex ($\chi^2(6) = 6.84$, $P = 0.34$), and no dose × sex interaction effect ($\chi^2(6) = 7.21$, $P = 0.30$); i.e., the effects of dose did not vary significantly across the sexes.

Although the US EPA has historically assessed dose–response data for male and female animals separately, combining data across sex is consistent with recent BMD guidelines that state, "Datasets that are statistically and biologically compatible may be combined prior to dose–response modeling, resulting in increased confidence, both statistical and biological, in the calculated BMD" (US EPA, 2012). Using data for both sexes increases the number of observations for dose–response modeling, which allows for better characterization of the dose–response relationship. In addition to using data from both male and female mice, it was also possible to use data from each intestinal segment because the NTP study provided incidence

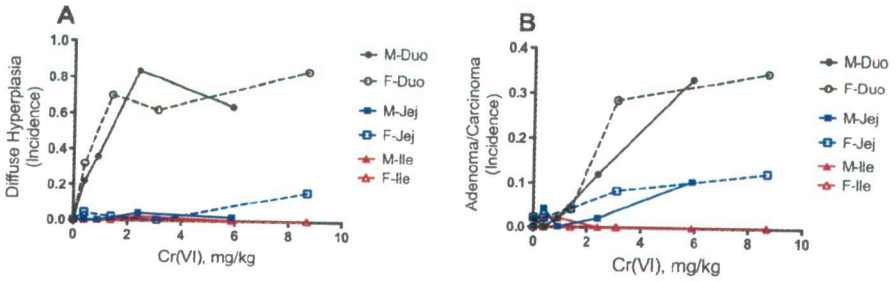

Figure 1. Dose–response of key intestinal lesions in mice from the NTP (2008b) 2-year bioassay. (A) Incidence of diffuse hyperplasia in the duodenum, jejunum and ileum of male and female mice. (B) Combined incidence of adenomas and carcinomas in the duodenum, jejunum and ileum of male and female mice. Duo, duodenum; F, female; Ile, ileum; Jej, jejunum; M, male.

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data in the duodenum, jejunum and ileum of each animal. With the availability of a rodent PBPK model (Kirman *et al.*, 2012), it was possible to predict the dose metric for chromium in each intestinal segment (see section on 'Hazard identification'). The overall process for RfD derivation is shown in Fig. 2.

Dose–response modeling

Applied study doses for relevant endpoints were converted to internal dose metrics in target tissues of mice using a previously published PBPK model (Kirman *et al.*, 2012). For each study dose, the PBPK model was used to estimate the internal dose of Cr(VI) entering each intestinal segment (duodenum, jejunum and ileum) (see section on 'Dose metric selection' and Appendix A). Dose–response modeling for adverse effects was conducted using US EPA's BMD Software (BMDS) v.2.3, using the suite of dichotomous models as well as the dichotomous-Hill model. Benchmark response (BMR) values of 5% and 10% extra risk were used to obtain BMD (BMD_x) values, along with their corresponding 95% lower confidence limit ($BMDL_x$), per US EPA recommendations (US EPA, 2012). The slopes were restricted to ≥ 1, which is done to prevent the estimated dose–response curve from taking on a biologically implausible very steep slope as the dose approaches zero. Model fits were judged using criteria such as *P*-values, scaled residuals, Akaike information criterion, parsimony and visual inspection. In addition to BMD modeling, CNR was conducted using GraphPad Prism 6 for Mac (http://www.graphpad.com) in an effort to characterize the relationship between dose, incidence and progression of disease (hyperplasia, adenoma, carcinoma) with a single Hill model:

$$Y = \text{Bottom} + (\text{Top-Bottom})/(1 + 10^{((\text{LogEC50-X}) \times \text{HillSlope})})$$

where,

$$\text{logEC50} = \text{logECF} - (1/\text{HillSlope}) \times \log(F/(100-F)); X = \log(\text{dose}); \text{and}$$

$F = 5$ (5% effective concentration)

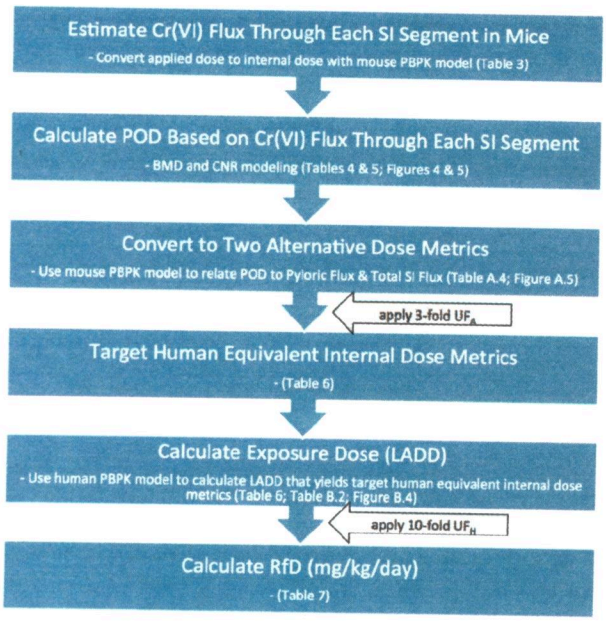

Figure 2. Process chart for derivation of RfD. LADD, lifetime average daily doses; POD, points of departure; RfD, reference dose.

Models were constrained by sharing model parameters such as Hill slope and maximum response. The effective concentration (EC) values and their 95% lower confidence limits (ECL) (computed using GraphPad) were compared to BMD and BMDL values (computed using BMDS). BMDL and ECL values based on internal doses were converted to human equivalent doses (HEDs) using a previously published human PBPK model for the disposition of ingested chromium (Kirman *et al.*, 2013). All PBPK modeling was performed in Advanced Continuous Simulation Language Extreme and its add-in for Microsoft Excel (asclX version 3; Aegis TG; http://www.acslx.com).

An RfD value was derived as follows. The mouse POD was first divided by the uncertainty factor (UF) for interspecies variation (UF_A) for two reasons: (1) this permits the calculation of a human equivalent POD value (calculated as mouse POD/UF_A), which can then be used to support a margin-of-exposure analysis, and (2) application of the UF_A term likely ensures that the interspecies extrapolation step is performed in a region where linear toxicokinetics are predicted in both species. The remaining UF values were then applied to HEDs corresponding to the mouse POD/UF_A as depicted in the equation below:

$$\text{RfD} = [\text{POD}/\text{UF}_A]_{\text{HED}}/[\text{UF}_H \times \text{UF}_D]$$

where,

RfD = (mg kg^{-1} day^{-1});

POD = Point of departure (expressed in terms of internal dose);

UF_A = uncertainty factor for interspecies variation (unitless);

UF_H = uncertainty factor for intraspecies variation (unitless); and

UF_D = uncertainty factor for database deficiencies (unitless).

Results

Hazard identification

This study focuses on the intestinal toxicity and carcinogenicity of Cr(VI) following ingestion, and thus does not discuss other effects of Cr(VI) outside the SI. To date, the most robust study of the oral toxicity and carcinogenicity of Cr(VI) was conducted by the NTP (NTP, 2008b; Stout *et al.*, 2009). The only lesion observed in the rat SI was histiocytic infiltration. In contrast, mice exhibited histiocytic infiltration and diffuse hyperplasia, and developed adenomas and carcinomas late in life. The NTP study authors concluded that the meaning of histiocytic infiltration was uncertain (NTP, 2008b), and our own MOA analysis did not consider this a critical effect (Thompson *et al.*, 2013). It is also notable that 90-day Cr(VI) studies in rats and mice revealed diffuse hyperplasia in the duodena of mice but not rats (NTP, 2007). It is well accepted that chemicals that induce cytotoxicity and cell proliferation in shorter-term bioassays are often carcinogenic in longer-term bioassays (Ames *et al.*, 1993; Boobis *et al.*, 2009; Cohen, 2010; Gaylor, 2005). We recently showed that Cr (VI) concentrations carcinogenic in mice induce villous cytotoxicity and crypt cell proliferation after only 7 days of exposure (Thompson *et al.*, 2011b). As outlined in the following section, recent studies strongly support that diffuse hyperplasia is a major risk factor (i.e., key event) in the development of intestinal cancer.

Mode of action for intestinal neoplasms

To investigate the MOA for intestinal carcinogenesis, a series of studies were conducted to collect histological, biochemical, toxicogenomic and pharmacokinetic data in the rodent SI (Kirman *et al.*, 2012; Kirman *et al.*, 2013; Kopec *et al.*, 2012a,2012b; O'Brien *et al.*, 2013; Proctor *et al.*, 2012; Thompson *et al.*, 2011a,2011b, 2012a,2012b,2012c). These data were evaluated along with other relevant literature (including the NTP study findings) to develop a MOA for intestinal carcinogenesis (Thompson *et al.*, 2013). The overall weight of evidence supports a cytotoxic MOA with the following key events: absorption of Cr(VI) from the intestinal lumen. villous cytotoxicity. compensatory crypt hyperplasia, and crypt cell mutagenesis (expansion of spontaneous mutations in the crypt cells as a consequence of the constant proliferative pressure).

Table 1 summarizes the concentrations at which significant changes in endpoints relevant to the MOA occurred in the 90-day drinking water study by Thompson *et al.* (2011b). At $\geq$ 5 mg l^{-1} Cr(VI), there were significant increases in duodenal chromium levels. At these same concentrations, significant changes in the GSH/GSSG ratio (a measure of redox status) were observed. Concentrations $\geq$ 20 mg l^{-1} Cr(VI) were accompanied by large increases in the number of mRNA transcripts that were significantly altered, as well as signs of cytoplasmic vacuolization in the intestinal villi. At $\geq$ 60 mg l^{-1} Cr(VI) (i.e., carcinogenic concentrations in the NTP 2-year bioassay), crypt cell proliferation was increased. Importantly, cytogenetic damage was not observed in duodenal crypts at any dose, nor were there any Cr(VI)-related increases in *K-ras* codon 12 GAT mutant frequency (O'Brien *et al.*, 2013). Because *K-ras* codon 12 GAT mutant frequency has been shown to be a reporter gene for mutations occurring in other oncogenes (Parsons *et al.*, 2012), the absence of Cr(VI)-induced increases in *K-ras* codon 12 GAT mutant frequency further supports a nonmutagenic MOA. Because the intestinal stem cells reside in the crypts below the mucosal surface, the apparent absence of toxicity and genetic damage in crypt cells following subchronic exposure to carcinogenic concentrations of Cr(VI) indicates that the intestinal tumors arose from chronic tissue damage and regenerative hyperplasia, rather than from direct interaction with DNA of crypt stem cells.

Figure 3 shows the dose–response for intestinal endpoints in male and female mice from the NTP study on an internal dose basis (described in the section on 'Dose metric selection').

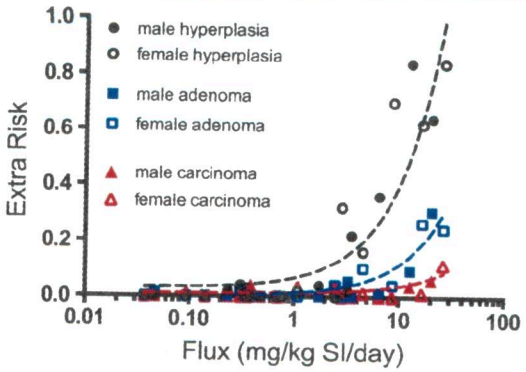

Figure 3. Dose–response of key intestinal endpoints from the small intestines of mice in the NTP (2008b) 2-year bioassay. Filled and open shapes represent data from male and female mice, respectively. The *x*-axis is expressed in terms of flux (i.e., the mg of Cr(VI) estimated to pass through each intestinal segment per day) (see text for details). The lines represent linear regression (*x* is log scale) through combined incidence. These plots are not used for quantitative dose–response modeling, but rather to show the progression of hyperplasia, adenomas and carcinomas. SI, small intestine.

Importantly, the term diffuse hyperplasia in the NTP study included both damage to villi and crypt proliferation. Clearly, intestinal diffuse hyperplasia occurred at lower doses (i.e., preceded) than did tumorigenic responses. Because intestinal diffuse hyperplasia is a precursor to tumor formation, preventing diffuse hyperplasia should preclude increased tumor formation in the intestine. Thus, an oral RfD that is protective of intestinal diffuse hyperplasia would also be protective of cancer.

Dose–response analysis

Critical effect selection

Diffuse hyperplasia and tumor formation data from the NTP 2-year bioassay were selected for dose–response analysis (NTP, 2008b). Table 2 summarizes the dose–response data set recently used to model these two endpoints based on applied dose (i.e., mg kg^{-1} bodyweight) (US EPA, 2010). However, with the availability of newly developed PBPK models, it was possible to assign the incidence data for diffuse hyperplasia and tumors to each intestinal segment (i.e., duodenum, jejunum, ileum). In

Table 1. Summary of mode of action study findings in mice exposed to Cr(VI)

Sodium dichromate dihydrate (mg l^{-1})	0	0.3[a]	4[a]	14	60	170	520
Cr(VI) (mg l^{-1})	0	0.1[a]	1.4[a]	5	20	60	180
Cr in duodenum	–	–	–	+	+	+	+
Redox changes	–	–	–	+	+	+	+
Gene changes	–	–	–	–	+	+	+
Villus toxicity	–	–	–	–	+	+	+
Crypt proliferation	–	–	–	–	–	+	+
Crypt cytogenetic damage	–	–	–	–	–	–	–
K-*ras* mutations	–	–	–	–	–	–	–
Preneoplastic lesions	–	–	–	–	–	–	–

[+] indicates doses where effects differed significantly from control; –, indicates no effect was observed.
[a] Cr(VI) concentrations not included in the National Toxicology Program studies.

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Table 2. Dose–response data sets for mouse small intestine effects using applied dose (US EPA, 2010)

Diffuse hyperplasia					Adenomas/carcinomas				
Segment	Sex	(mg kg^{-1} day^{-1})[a]	n	Hyperplasia	Segment	Sex	(mg kg^{-1} day^{-1})[a]	n	Tumor[b]
d	f	0	50	0	d, j, i	m	0	49	1
d	f	0.38	50	16	d, j, i	m	0.38	49	3
d	f	1.4	50	35	d, j, i	m	0.91	49	2
d	f	3.1[c]	50	31	d, j, i	m	2.4	50	7
d	f	8.7[c]	50	42	d, j, i	m	5.9	48	20

d, duodenum; f, female; i, ileum; j, jejunum; m, male.
[a]Based on applied dose (mg Cr(VI) per kg bodyweight per day).
[b]Based on combined incidence of adenomas and carcinomas.
[c]Data points were dropped to achieve benchmark dose model fits (see text for discussion).

doing so, a far more robust dose–response data set (24 treatment groups spanning a range of nearly three orders of magnitude) was generated as compared to that based on administered dose to a single sex (i.e., four treatment groups spanning approximately one order of magnitude).

Table 3 shows the incidence data for diffuse hyperplasia and tumor formation (all incidence data are from the NTP 2-year bioassay) assigned to the predicted flux of Cr(VI) into each intestinal segment. The number of observations for hyperplasia and tumors differs, because, consistent with the approach used in US EPA (2010), we excluded animals that died before the appearance of the first intestinal tumor (typically one or two animals per treatment group). [Poly-k adjustments were not used because: (1) Cr(VI) had no effect on survival (NTP, 2008b);

Table 3. Dose–response data set for mouse small intestine effects using internal dose

Hyperplasia					Tumor incidence					
Segment	Sex	Flux (mg kg^{-1} SI day^{-1})[a]	n	Hyperplasia	Segment	Sex	Flux (mg kg^{-1} SI d^{-1})[a]	N	Adenoma	Carcinoma
d, j, i	m, f	0	300	0	d, j, i	m, f	0	294	1	1
i	f	0.0377	50	0	i	f	0.0377	50	0	0
i	m	0.0469	50	0	i	m	0.0469	49	1	0
i	m	0.0943	50	0	i	m	0.0943	49	0	1
i	f	0.143	50	0	i	f	0.143	49	0	0
i	m	0.236	50	1	i	m	0.236	50	0	0
j	f	0.312	50	2	j	f	0.312	50	1	0
i	f	0.351	50	0	i	f	0.351	49	0	0
j	m	0.389	50	0	j	m	0.389	49	0	2
i	m	0.485	50	0	i	m	0.485	48	0	0
i	f	0.701	50	0	i	f	0.701	49	0	0
j	m	0.760	50	0	j	m	0.760	49	0	0
j	f	1.10	50	1	j	f	1.10	49	0	2
j	m	1.75	50	2	j	m	1.75	50	0	1
j	f	2.48	50	0	j	f	2.48	49	2	2
d	f	2.88	50	16	d	f	2.88	50	0	0
j	m	3.29	50	1	j	m	3.29	48	3	2
d	m	3.56	50	11	d	m	3.56	49	0	0
j	f	4.58	50	8	j	f	4.58	49	5	1
d	m	6.50	50	18	d	m	6.50	49	1	0
d	f	8.69	50	35	d	f	8.69	49	2	0
d	m	12.8	50	42	d	m	12.8	50	5	2
d	f	16.6	50	31	d	f	16.6	49	13	1
d	m	20.5	50	32	d	m	20.5	48	15	3
d	f	26.6	50	42	d	f	26.6	49	12	6

d, duodenum; f, female; i, ileum; j, jejunum; m, male; SI, small intestine.
[a]Based on mg Cr(VI) per kg of small intestine (SI) segment per day.
These values are also reported in Appendix Table A.3.

(2) US EPA did not use a poly-k adjustment in their risk assessment of Cr(VI) (US EPA, 2010); and (3) the primary effect of concern was non-neoplastic (i.e., diffuse hyperplasia).] Because male and female mice in each treatment group had unique internal dose metrics for each intestinal segment, the sample size (n) for each observation was 50, except in cases where animals died prematurely. The n for the control groups (i.e., zero internal dose) is the total number of intestinal segments (three per animal) for male and female control mice combined. It is immediately apparent in Table 3 that the segment with the lowest flux (i.e., ileum) characterizes the low end of the dose–response curve, and the tissue with the highest flux (i.e., duodenum) characterizes the upper end of the dose–response curve. These data are consistent with the NTP study findings of the rank of adverse effects in the intestine (duodenum > jejunum >> ileum) (NTP, 2008b; Stout *et al.*, 2009), as well as the chromium tissue burden measured in each intestinal segment (Kirman *et al.*, 2012; Thompson *et al.*, 2011b).

Dose metric selection

The selection of an appropriate dose measure requires careful consideration of the MOA (US EPA, 2006). A number of candidate internal dose measures are available for assessing the dose–response relationship for small intestinal tumors and diffuse hyperplasia in the mouse, including those for different valence states [Cr(III), Cr(VI), total Cr]. Using a published PBPK model (Kirman *et al.*, 2012), the Cr(VI) concentration in the intestinal lumen and Cr(VI) flux into tissues may be predicted for mice and used as internal dose measures. With respect to valence state, dose measures for Cr(III) and total Cr are not considered useful, for two reasons. First, based on the proposed MOA for mouse SI tumors (Thompson *et al.*, 2013), Cr(III) is not causally related to the formation of tumors. Second, measures of Cr(III) and total Cr do not appear to be useful for predicting tumor response, because model predictions for the Cr(III) tissue doses (for which no neoplastic or non-neoplastic intestinal pathology was observed) from NTP's bioassay for chromium picolinate (NTP, 2008a) overlap the dose regions associated with measurable effects in mice from NTP's Cr(VI) bioassay (NTP, 2008b) (data not shown). For these reasons, internal dose measures for Cr(VI) were selected for dose–response assessment.

For tumors in the mouse SI, potential candidate dose measures include those for Cr(VI) concentration (e.g., in the lumen or tissue of the small intestines) or Cr(VI) flux (e.g., Cr(VI) leaving the stomach lumen or entering into the duodenum, jejunum, and ileum). In addition to MOA considerations, selection of an appropriate dose measure should consider confidence in the PBPK model predictions. Greater confidence is placed on intestinal tissue dose predictions, because these are underpinned by measurements of total Cr in intestinal tissue (Kirman *et al.*, 2012), while corresponding measurements in gastrointestinal lumen are not available. We consider Cr(VI) tissue flux, defined as the amount (mg) of Cr(VI) entering intestinal tissue sections from the gastrointestinal lumen (normalized to per kg intestinal tissue per day), to be the best available dose metric for risk assessment, for the following reasons. First, tissue flux estimates are not affected by subsequent processes (intracellular reduction, transfer to blood, intestinal tissue sloughing) that are more uncertain in the model, and therefore can be predicted with greater confidence than tissue concentration in the PBPK model. Second, although total Cr tissue concentration data are available for rodents (Kirman *et al.*, 2012), such data are not available for humans. Because the SI serves as the primary site of absorption, estimates of Cr(VI) flux can be linked to measures of total Cr in human tissues and urinary excretion (see text below). As shown in Fig. 3, visual inspection of the NTP mouse SI data indicate that the tissue flux of Cr(VI) into each intestinal segment (duodenum, jejunum, and ileum) indeed provides an excellent dose–response concordance of the hyperplasia and tumor response in the mouse SI. Moreover, the plots clearly support that male and female mice responded similarly to Cr(VI) as was indicated by responses on a mg kg^{-1} bodyweight basis in Fig. 1.

Dose–response modeling

Benchmark dose modeling

BMD modeling was conducted on three endpoints for mouse SI from the NTP study: (1) incidence of diffuse hyperplasia; (2) incidence of adenomas; and (3) incidence of carcinomas. For modeling hyperplasia data, we omitted the jejunum for the following reasons. First, unlike tumor incidence that was assessed grossly across each intestinal segment, hyperplasia incidence was assessed microscopically by a single 5 μm biopsy taken at the approximate midpoint of each intestinal segment. The duodenum and ileum are each ~9 cm long whereas the jejunum is ~19 cm long—implying that the biopsy taken in the jejunum may not accurately reflect hyperplasia in the proximal jejunum. Second, pharmacokinetic data indicate that there is a proximal-to-distal decrease in intestinal tissue Cr concentrations between the duodenum and ileum (i.e., within the jejunum) (Kirman *et al.*, 2012; Thompson *et al.*, 2011b). Considering that the modeled flux values in the jejunum do not account for this gradient and that a single 5 μm section along a 19 cm tube was used to score hyperplasia in the jejunum, there is considerable uncertainty with regard to incidence data of jejunal hyperplasia. In contrast, the high Cr tissue concentrations in the duodenum were associated with hyperplasia and tumor formation, and the very low Cr tissue concentrations in the ileum were not associated with hyperplasia or tumors. Therefore, the dose–response modeling of hyperplasia was conducted without the jejunal data. Because biopsies for hyperplasia at the midpoint of the jejunum may underestimate the incidence of hyperplasia in the proximal jejunum, omission of these data from the dose–response modeling may be viewed as health protective because inclusion of jejunal data would only serve to increase the predicted POD values, albeit with poorer model fits.

BMD modeling with the duodenal and ileal data resulted in good fitting models with respect to P-value (i.e., > 0.1); however, the scaled residuals for most all models were outside EPA's recommended range of ± 2. This indicates that although the models fit the data, they may not fit optimally near the BMD. Notably, the scaled residual value for best fitting model (namely 2.3) only slightly exceeded this cutoff. Nevertheless, we determined that the scaled residuals were acceptable at a BMR of 5% (i.e., lower down the dose–response curve). Selecting a lower BMR is justifiable because the BMR is still within the observable range of data (US EPA, 2012), and is furthermore health protective. This resulted in a $BMDL_{05\text{-}flux}$ value of 0.84 mg kg^{-1} SI day^{-1} (Table 4; Fig. 4A).

As mentioned above, tumors were assessed across the entire length of each intestinal segment, and thus tumor incidence data for the jejunum were modeled together with the

Table 4. Summary of BMD model fits for diffuse hyperplasia and intestinal tumors

Endpoint	Segment	Sex	$BMD_{05\text{-}flux}$ ($BMD_{10\text{-}flux}$)	$BMDL_{05\text{-}flux}$ ($BMDL_{10\text{-}flux}$)	*P*-value[a]	Doses[b] drop/tot
Diffuse hyperplasia	d, i	m, f	1.2 (1.8)	0.84 (1.4)	0.16	3/16
Adenomas	d, j, i	m, f	6.1 (10.1)	4.5 (8.3)	0.10	0/24
Carcinomas	d, j, i	m, f	19.7 (26.2)	16.4 (21.8)	0.13	0/24

d, duodenum; f, female; i, ileum; j, jejunum; m, male.
[a]$P \geq 0.1$ indicates good model fit.
[b]Number of dropped high doses/number of total possible doses (not including control); high doses were dropped (sequentially) until *P*-value for model fit was ≥0.1.

duodenum and ileum. Consistent with the plots in Fig. 3, the $BMDL_{05\text{-}flux}$ values for adenomas were lower than for carcinomas (e.g., 4.5 vs. 16.4 mg kg^{-1} SI day^{-1}; Table 4). These findings are consistent with the notion that intestinal adenocarcinomas are thought to be the result of a progression from adenomas to carcinomas (Grady and Carethers, 2008; Greaves, 2012). Notably, modeling the combined incidence for adenomas and carcinomas resulted in models with *P*-values for model fit less than 0.1 (data not shown). The BMD plot for the incidence of adenomas is shown in Fig. 4(B).

Constrained nonlinear regression

In addition to BMD modeling, CNR was conducted to obtain EC_{05}, EC_{10}, ECL_{05} and ECL_{10} values for diffuse hyperplasia and tumor formation using a Hill model. This analysis is not meant to supplant the BMD modeling results, but rather to assess their validity using different modeling approaches. Specifically, CNR allows for finding model solutions to multiple data sets simultaneously by sharing information from each data set. In this way, the dose–response relationships for hyperplasia, adenoma and carcinoma can be characterized using a single model. By sharing parameters, CNR modeling assumes that the incidence of small intestinal tumors in the low-dose region is proportional to the incidence of diffuse hyperplasia. We compared the ECL values for hyperplasia (in duodenum and ileum), adenomas (in all segments) and carcinomas (in all segments) by constraining the models to share the same Hill slope and maximal response parameters (Fig. 5). Overall, the ECL values were in remarkably close agreement with the BMDL values reported in Table 4. For example, the ECL_{05} values for hyperplasia, adenomas and carcinomas were respectively 0.6, 4.2 and 9.4 mg kg^{-1} SI day^{-1} (Table 5), which are similar to the $BMDL_{05}$ values of 0.8, 4.5 and 16.4 mg kg^{-1} SI day^{-1} (Table 4).

Interspecies extrapolation

Internal doses corresponding to the PODs for small intestinal hyperplasia and tumors in mice can be extrapolated to humans using the human PBPK model developed for Cr (Kirman *et al.*, 2013). However, limitations in the available human data, specifically the lack of data regarding the relative uptake of chromium in the human duodenum, jejunum and ileum, preclude the use section-specific flux estimates for interspecies extrapolation. Therefore, two measures of total Cr(VI) flux were identified as internal dose surrogates to be used to extrapolate from mice to humans: (1) the flux of Cr(VI) leaving the stomach lumen (normalized to per liter of SI tissue per day (mg Cr(VI) l^{-1} day^{-1}) (which we term "pyloric flux" for simplicity), and (2) the flux of Cr(VI) entering the total SI tissue (normalized to per kg SI tissue per day (mg Cr(VI) l^{-1} day^{-1}) (which we term "intestinal flux" for simplicity). In the mouse, the latter estimate is calculated as the segment mass-weighted average for Cr(VI) flux in total SI. Both measures of Cr(VI) flux were related to total SI tissue response (i.e., including the duodenum, jejunum and ileum

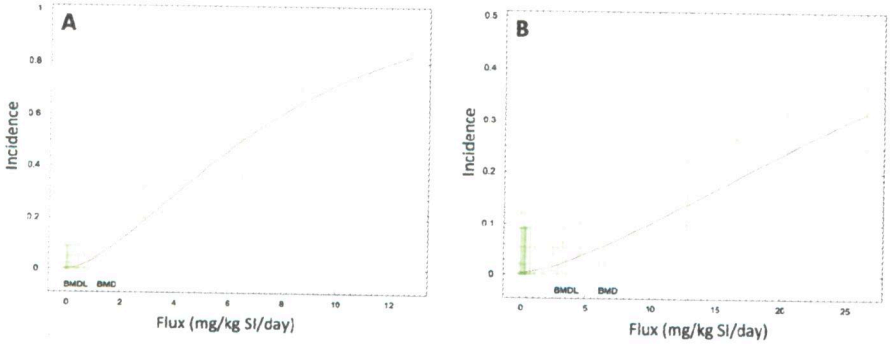

Figure 4. BMD modeling of the hyperplasia incidence (A) and adenoma incidence (B) in the mouse small intestine as a function of internal dose (mg Cr(VI) per kg SI per day). Incidence data are from NTP (2008b). BMD, benchmark dose; BMDL, benchmark dose values and their 95% lower confidence limits; SI, small intestine.

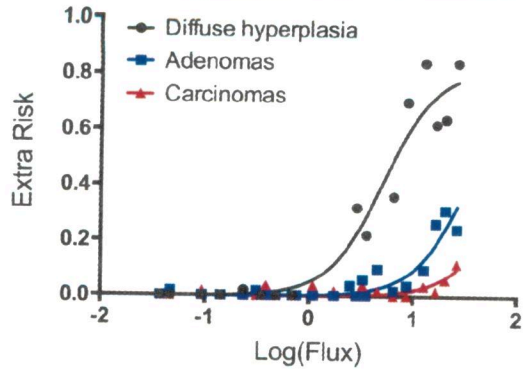

Figure 5. Constrained nonlinear regression of incidence data in NTP 2-year bioassay. Effective concentration values and their 95% lower confidence limits were computed for hyperplasia, adenomas and carcinomas by constraining the models to share the Hill slope and maximal response. Corresponding effective concentration values and their 95% lower confidence limits, Hill slopes and R^2 values are shown in Table 5. For tumors, data from all SI segments were used whereas only the duodenum and ileum were used for hyperplasia (see text).

together) in the mouse using an assumption of dose additivity (i.e., total SI response is predicted using the sum of the section flux estimates). In this way, for example, a BMD_{05} value corresponds to the Cr(VI) internal dose that produces a 5% response rate in the total SI, which is composed of relative section contributions of approximately 4.4% response in mouse duodenum, 0.55% response in mouse jejunum and 0.05% response in mouse ileum. The pyloric flux surrogate [flux of Cr(VI) leaving the stomach lumen] can be predicted with a reasonable degree of certainty in humans, because it depends primarily on our understanding of gastric transit rates obtained from the published literature (ICRP, 2002) and the reduction of Cr(VI) in human gastric contents that were measured *ex vivo* (Kirman *et al.*, 2013). Use of the pyloric flux surrogate for interspecies extrapolation assumes that the toxicokinetic processes for Cr(VI) in SI lumen and tissue are qualitatively and quantitatively similar for mice and humans. The intestinal flux surrogate [flux of Cr(VI) entering the total SI] can also be predicted with a reasonable degree of certainty, because it depends on available human toxicokinetic data (Kirman *et al.*, 2013). The key assumptions for this flux surrogate are (1) that the SI serves as the primary site of Cr absorption, and therefore, measurements of Cr in human plasma and urine (obtained from numerous Cr pharmacokinetic studies published in the literature) predominantly reflect Cr that had been absorbed in the SI (but cannot differentiate absorption via each intestinal segment), and (2) that the toxicokinetic processes for Cr(VI) when it reaches small intestinal tissue are qualitatively and quantitatively similar for mice and humans. All three estimates of Cr(VI) flux used in this assessment are depicted graphically in Appendix A (see Fig. A.2).

Human equivalent lifetime average daily doses ($LADD_{HE}$) that correspond to the mouse internal POD values were calculated using the human PBPK model by considering variation in toxicokinetic processes for Cr(VI) as a function of age using the following five age groups: (1) neonate (0–3 months); (2) infant/child (0.25–6 years); (3) youth (6–18 years); (4) adult (18–60 years); and (5) elderly (60–75 years). Human exposures via drinking water were considered to be of primary importance for Cr(VI), and therefore, age group-specific exposure scenarios were developed based on the drinking water consumption pattern data (Barraj *et al.*, 2009). For the purposes of modeling, the average number of drinking water events per day for each age group from this study was rounded up to the next-highest even number, with half of the exposure events assumed to occur on an empty stomach (i.e., fasted state between meals), and the other half of the exposure events assumed to occur in a fed state (e.g., water consumed with meals). Exposure events (four to six per day) were defined to occur over 1 h intervals, based on the hourly consumption pattern data (Barraj *et al.*, 2009). In addition to exposure-event scheduling, several gastrointestinal parameters were modeled to vary over the course of a day, including gastric pH, gastric transit half-time and gastric reducing equivalents. Details on the application of the human PBPK model for chromium to risk assessment are summarized in Appendix B. Human equivalent LADDs corresponding to the mouse POD values for small intestinal hyperplasia and tumors were calculated as the time-weighted average for each age group, based on the two Cr(VI) flux surrogates (pyloric flux and total intestinal flux).

Chronic oral reference dose derivation

A range of $LADD_{HE}$ values were calculated for diffuse hyperplasia and tumor formation based on two modeling approaches (BMD modeling and CNR) and two human dose surrogates (pyloric flux and total intestinal flux) (Appendix B). Because species

Table 5. EC_{10} and ECL_{10} values using constrained nonlinear regression[a]

	Segment	Sex	$EC_{05\text{-flux}}$ ($EC_{10\text{-flux}}$)	$ECL_{05\text{-flux}}$ ($ECL_{10\text{-flux}}$)	Hill slope[b]	Max[b]	R^2
Diffuse hyperplasia	d, i	m, f	0.88 (1.4)	0.56 (0.98)	1.7	0.82	0.94
Adenoma	d, j, i	m, f	5.9 (9.2)	4.2 (7.3)	1.7	0.82	0.85
Carcinoma	d, j, i	m, f	15.1 (23.5)	9.4 (14.5)	1.7	0.82	0.57

d, duodenum; f, female; i, ileum; j, jejunum; m, male.
[a]The minimum parameter was constrained to be zero; the maximum parameter was constrained to be between 0 and 1 (and shared); the Hill slope parameter was constrained to be shared.
[b]Values are global values.

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Table 6. Human LADD values corresponding to mouse POD values

		Internal dose (mg Cr(VI) kg^{-1} SI day^{-1})			External dose (mg Cr(VI) kg^{-1} BW day^{-1})	
		Mice	Human		Human LADD[b]	
Response	POD	SI sectional flux	Pyloric flux[a]	Total SI flux[a]	Pyloric flux	Total SI flux
Hyperplasia	$BMDL_{05}$	0.84	0.75	0.092	0.061	0.059
	ECL_{05}	0.56	0.49	0.061	0.041	0.040
Adenoma	$BMDL_{05}$	4.5	4.1	0.49	0.20	0.18
	ECL_{05}	4.2	3.8	0.46	0.19	0.17
Carcinoma	$BMDL_{05}$	16	15	1.8	0.44	0.37
	ECL_{05}	9.4	8.6	1.0	0.31	0.27

BMDL, benchmark dose values and their 95% lower confidence limits; ECL, effective concentration values and their 95% lower confidence limits; LADD, lifetime average daily doses; POD, points of departure; SI, small intestine.
[a]This value has already been divided by a threefold UF_A (see text and Appendices A and B).
[b]The LADD is a time-weighted average for five age groups (see Appendix B).

Table 7. Oral RfD and DWEL values for Cr(VI)

Endpoint	$LADD_{HE}$ (mg kg^{-1} day^{-1})	UF_H	RfD (mg kg^{-1} day^{-1})	DWEL (μg l^{-1})
Diffuse hyperplasia	0.06[a]	10[b]	0.006	210[c]

DWEL, drinking water equivalent level; LADD, lifetime average daily doses; RfD, reference dose.
[a]Mean $BMDL_{05}$ from Table 6 (a threefold UF_A is already incorporated).
[b]See text for discussion.
[c]DWEL = RfD mg kg^{-1} day^{-1} × 70 kg ÷ 2 l

differences in pharmacokinetics were accounted for by using rodent and human PBPK models, the BMDL and ECL values were each reduced threefold to account for potential remaining uncertainties in pharmacodynamics when extrapolating from mice to humans. The human PBPK model was then used to estimate external doses to humans that result in these two internal dose metrics for each outcome of interest (i.e., hyperplasia, adenomas and carcinomas). Values based on $BMDL_{05}$ and ECL_{05} are shown in Table 6. Values based on a 10% response can be found in Appendix B.

The multiple dose–response approaches described herein support a conclusion that diffuse hyperplasia is a more sensitive endpoint than tumor formation. Moreover, the MOA for Cr(VI)-induced intestinal tumors suggests that protection against the precursor effect of diffuse hyperplasia will also be protective of intestinal neoplasms. Therefore, only $LADD_{HE}$ values for diffuse hyperplasia were considered for RfD derivation. The $LADD_{HE}$ values for diffuse hyperplasia based on BMD modeling and CNR ranged from 0.04 to 0.06 mg kg^{-1} bodyweight day^{-1} (Table 6). Because the BMD methodology is recommended by US EPA for dose–response modeling, only the mean $LADD_{HE}$ values based on the $BMDL_{05}$ values were considered for RfD derivation at this time. This mean $LADD_{HE}$ value was reduced by a 10-fold intraspecies uncertainty factor (UF_H) to account for human variability in Cr(VI) disposition and pharmacodynamic responses. A database uncertainty factor (UF_D) was deemed unnecessary due to the availability of reproductive and developmental toxicity studies in multiple species; adverse effects from these studies were less sensitive than those in the gastrointestinal tract (US EPA, 2010). The resulting chronic RfD value is 0.006 mg kg^{-1} day^{-1}, which is considered protective of the noncancer and cancer effects of Cr(VI) in the SI (Table 7).

Discussion

A series of recent studies into the MOA of Cr(VI) in the small intestine indicate that the weight of evidence supports a nonmutagenic MOA based on chronic intestinal wounding leading to compensatory regenerative crypt hyperplasia and, ultimately, intestinal carcinogenesis (Thompson *et al.*, 2013). These findings establish that the MOA for Cr(VI)-induced intestinal tumors is not linear in the low-dose region. Concentrations of Cr(VI) that do not induce cytotoxicity and regenerative crypt proliferation are unlikely to increase the risk of intestinal cancer (see Fig. 3). For carcinogens that induce cancer through such nonlinear mechanisms, the US EPA has recommended development of RfD values (US EPA, 2005). An RfD is defined by the US EPA as "an estimate (with uncertainty spanning perhaps an order of magnitude) of a daily exposure to the human population (including sensitive subgroups) that is likely to be without an appreciable risk of deleterious effects during a lifetime." Moreover, it is said to "provide quantitative information for use in risk assessments for health effects known or assumed to be produced through a nonlinear (possibly threshold) mode of action" (http://www.epa.gov/iris/help_ques.htm). In this regard, RfD values based on intestinal irritation induced by captan and folpet have been deemed protective of intestinal cancer (Gordon, 2007; US EPA, 2004).

The RfD developed herein is derived from a very rich data set. By using a rodent PBPK model to estimate target tissue doses achieved in multiple intestinal segments of all treated animals (male and female) in the 2-year bioassay, incidence values at multiple dose levels could be used to create a robust dose–response curve. Examining each intestinal segment within the proper context of tissue dose, dose–response data for the segment achieving the lowest internal dose (i.e., ileum) can be used to improve our understanding of the potential low-dose risks associated with the high internal doses achieved in upper segments of the intestine (i.e., duodenum and jejunum). Using this robust data set, standard BMD modeling was used to calculate BMDL values for diffuse hyperplasia based on internal dose (i.e., SI section flux). In addition, CNR was employed to develop ECL values for the same endpoint. Although CNR is often used to share parameters for the same endpoint (e.g., receptor activation by two congeners), it could be used, in theory, to share parameters between two related phenomena when plotted on the same axes (i.e., dose vs. incidence). Notably, the POD values using BMD and CNR modeling were remarkably similar. The range of POD estimates for each endpoint were quite narrow (i.e., < 2-fold; Table 6). Obtaining similar findings using multiple modeling approaches strengthens the confidence in the results. Moreover, these POD values for hyperplasia, adenomas and carcinomas are consistent with the progression of intestinal cancer (Grady and Carethers, 2008; Greaves, 2012). To our knowledge, this is the first example of using CNR to share parameters to characterize the progression of disease (e.g., hyperplasia to adenoma to carcinoma); additional case examples are needed to assess the general applicability of this approach in risk assessment.

The proposed RfD (0.006 mg kg^{-1} day^{-1}) is less than 10-fold higher than the RfD previously derived by US EPA (2010). In their draft assessment, US EPA's BMD modeling of diffuse hyperplasia based on applied dose (mg kg^{-1} bodyweight) in female mice resulted in an RfD of 0.0009 mg kg^{-1} day^{-1} [0.09 mg kg^{-1} (the $BMDL_{10}$ for diffuse hyperplasia) divided by 10-fold uncertainty factors for UF_A and UF_H, each]. A major difference between these RfD values is the treatment of the critical effect. US EPA analyzed diffuse hyperplasia in males and females separately, despite evidence that this effect was similar in both sexes (Figs 1 and 3). When modeling diffuse hyperplasia in this manner based on applied dose, acceptable BMD modeling fits could only be achieved by dropping the two highest dose groups from the analysis – leaving only two treatment doses and a control group for quantitative modeling (Table 2). In contrast, the modeling approach described herein uses an internal dose metric that allows for the derivation of PODs based on 13 data points normalized across intestinal segments (duodenum and ileum) for diffuse hyperplasia, and 24 data points for tumor formation (in duodenum, jejunum and ileum). Another difference in the RfD values proposed herein and those by US EPA is the application of uncertainty factors. US EPA applied 10-fold default values each for UF_A and UF_H (US EPA, 2010). The newly developed PBPK models allows for a reduction in the UF_A to threefold due to accounting for species differences in the disposition of Cr(VI). In addition, the human PBPK model allows for development of an RfD based on a LADD, which includes life-stage-specific adjustments to pharmacokinetic aspects of Cr(VI) disposition [e.g., stomach pH variability, which affects the rates of Cr(VI) reduction throughout life] and thus provides a more scientifically robust quantitative description of dose. Nevertheless, we conservatively included a full 10-fold UF_H value to account for interindividual human variability.

The use of the rodent PBPK model to convert the applied doses in the animal study to an internal tissue dose metric, and the human PBPK model to convert the PODs to HEDs, offers a vast improvement over using the applied study doses for deriving RfDs. Some sources of uncertainty remain in the PBPK models for chromium in mice and humans, many of which have been discussed previously (Kirman *et al.*, 2013; Kirman *et al.*, 2012). With respect to the human PBPK model, the data available for chromium in exposed humans are limited to plasma, erythrocytes and urine (Kirman *et al.*, 2013), and for this reason, the Cr(VI) flux estimates into the total SI from the human model are uncertain. To address this limitation, a second flux estimate [Cr(VI) leaving the stomach], which can be estimated with a greater degree of certainty as it depends on parameters that are relatively well characterized (human stomach transit times and human gastric reduction rates), was included in the assessment. The two Cr(VI) flux estimates evaluated (pyloric and intestinal flux) have separate bases and assumptions, but nevertheless result in nearly identical estimates of risk, differing by less than a factor of 2. Hence, this source of uncertainty is relatively small.

One of the largest sources of uncertainty relates to the relative timing of Cr(VI) exposure events and normal diurnal variation in gastrointestinal parameters such as pH, reducing equivalents and gastric transit due to the presence or absence of food in the stomach. For the human equivalent doses presented above, an assumption was made that 50% of the drinking water exposure events per day occur during a fed state and 50% during a fasted state. Because some factors favor greater gastric reduction during the fed state (e.g., higher reducing equivalent concentrations, longer gastric transit half-life), while other factors favor greater gastric reduction during a fasted state (e.g., lower pH resulting in a higher rate of reduction), it is not obvious which state results in greater delivery of Cr(VI) to the SI. Model predictions suggest that assuming 100% of exposure events during a fasted state will result in slightly larger estimates of daily internal dose to the SI than estimated in this assessment (by a factor of approximately 2–5), while assuming 100% of exposure events during a fed state will result in slightly lower estimates of internal dose to the SI than estimated in this assessment (by a factor of approximately 20–50%) (Appendix B). However, neither of these extreme assumptions is likely to remain constant over a lifetime.

The rate of Cr(VI) reduction in human stomach fluid in the fed state in the human PBPK model is based on samples from fasted individuals at pH 5–7 because samples from fed individuals were not available for study of Cr(VI) reduction kinetics (Kirman *et al.*, 2013). It is known that the stomach pH increases immediately following a meal because the introduction of food dilutes acidic stomach fluid. Because we do not have data on the reduction rate in actual fed conditions, we have had to rely on reduction rate data for fasted individuals at a higher pH than normal fasting conditions, at which the pH is ~ 1.5. As such, the current model does not allow us to account quantitatively for any differences in reduction rate that might be expected with the release of gastric acid and enzymes that occur with

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the consumption of food. We expect that the Cr(VI) reduction rate may be underestimated for a fed state in the PBPK model, resulting in an overestimation of the transfer of Cr(VI) to the SI in fed conditions.

Although the assessment presented here specifically included modeling of different age groups, to account for differences in toxicokinetic factors as a function of age, it did not explicitly consider other conditions or disease states that may affect risk. For example, individuals who take proton-pump inhibitors (PPIs) are expected to have higher gastric pH levels, and because of the pH dependence of Cr(VI) reduction, have comparatively lower rates of Cr(VI) reduction in the gastric lumen when taking these medications. In fact, model predictions suggest that daily Cr(VI) flux estimates may be three- to fourfold higher among PPI users, based upon the pH profile of Atanassoff *et al.* (1995), than in individuals with normal stomach conditions. However, PPI medication is recommended for relatively short durations and as a result, the LADD value for PPI users is nearly identical to that for normal individuals. For example, assuming that an adult uses PPIs for 30 months (intermittently over a lifetime) (Dharmarajan *et al.*, 2008) and exhibit daily gastric pH consistent with previous reports (Atanassoff *et al.*, 1995), the model predicts that the lifetime average daily dose increases by approximately 7–10%. Because the variability in LADD estimates with PPI usage and with varying assumptions regarding water consumption patterns is small, the 10-fold UF_H used to calculate the RfD is considered to be adequately protective of these known variables of human sensitivity. Importantly, the use of our human PBPK model allows for the evaluation of sensitive life stages and conditions that otherwise could not be assessed quantitatively, and therefore increases confidence in the RfD.

Finally, Cr(VI) is prevalent in some US drinking water supplies at low concentrations (~1–5 $\mu g\ l^{-1}$) (AWWA, 2004; CDPH, 2011), and therefore, it is of significant public health interest to understand the potential cancer hazard associated with these typical exposures. The chronic drinking water equivalent level calculated from the RfD derived herein ($0.006\ mg\ kg^{-1}\ day^{-1}$), and the application of standard assumptions regarding drinking water consumption ($2\ l\ day^{-1}$) for a 70 kg individual, results in a drinking water concentration of 210 $\mu g\ l^{-1}$. This value is greater than the current federal MCL for total Cr of 100 $\mu g\ l^{-1}$ and is well above levels of Cr(VI) in drinking water supplies. Thus, typical concentrations of Cr(VI) in the US drinking water supply are not expected to increase the risk of intestinal cancer, and the current federal MCL of 100 $\mu g\ l^{-1}$ is protective against increased intestinal cancer risk.

Sponsors

The authors employment affiliations are as shown on the cover page. Both ToxStrategies and Summit Toxicology are private consulting firms providing services to private and public organizations on toxicology and risk assessment issues. The authors [CT, CK, DP, LH, SH, MH] have presented study findings in meetings with regulators including public meetings on behalf of the Cr(VI) Panel of the American Chemistry Council (ACC). DP has also been an expert in litigation involving Cr(VI), which was unrelated to this research or ACC.

Supporting Information

Supporting Information may be found in the online version of this article.

Acknowledgments

The authors thank Drs. Ted Simon, Deborah Barsotti and Heather Burleigh-Flayer for their thoughtful comments on an earlier version of this manuscript. The authors also thank the Toxicology Excellence for Risk Assessment (TERA) Expert Panel for overseeing the Cr(VI) MOA Research Program. The panel report is available at http://www.tera.org/Peer/Chromium/Chromium.htm.

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Bohn, Brent

From: Gibbons, Catherine
Sent: Friday, December 04, 2015 7:48 PM
To: Bohn, Brent
Subject: FW: California visit

From: Khan, Elaine@OEHHA [mailto:Elaine.Khan@oehha.ca.gov]
Sent: Wednesday, September 18, 2013 9:17 PM
To: Gibbons, Catherine <Gibbons.Catherine@epa.gov>
Subject: RE: California visit

Great!

From: Gibbons, Catherine [mailto:Gibbons.Catherine@epa.gov]
Sent: Wednesday, September 18, 2013 6:08 PM
To: Khan, Elaine@OEHHA
Subject: RE: California visit

That sounds great, thanks Elaine! I'll let you know closer to the date about when I think I can get there, I need to coordinate with my friend, but that should work fine! Thanks so much!

From: Khan, Elaine@OEHHA [mailto:Elaine.Khan@oehha.ca.gov]
Sent: Wednesday, September 18, 2013 7:33 PM
To: Gibbons, Catherine
Subject: RE: California visit

Hi, Catherine.

We're good to go for lunch – we've blocked off noon to 2 pm for that. I can meet up with you a bit earlier if you'd like and take you around our Oakland office, just let me know. We're at 1515 Clay St. (Elihou Harris Bldg), Oakland. Look forward to meeting you!

Elaine

From: Gibbons, Catherine [mailto:Gibbons.Catherine@epa.gov]
Sent: Wednesday, September 18, 2013 6:30 AM
To: Khan, Elaine@OEHHA
Subject: RE: California visit

Hi Elaine,

The time you suggested would be great, I'm free all day. I would certainly be honored to have lunch with Drs. Alexeeff and Zeise, but I won't be offended if they are too busy, I know around here most folks barely have time to eat at their desks! Thanks again and I'm looking forward to it!

Catherine

From: Khan, Elaine@OEHHA [mailto:Elaine.Khan@oehha.ca.gov]
Sent: Tuesday, September 17, 2013 6:45 PM
To: Gibbons, Catherine
Subject: RE: California visit

Hi, Catherine!

I'm so glad you'll be in Oakland on the 26th! George Alexeeff (our Director) and Lauren Zeise are usually in our Oakland office on Thursdays, so I'll try to see if we can set up lunch with them. How does that sound? Do you think you'll be available from about 11 am to 2 pm? Let me know and I'll try to set something up. Thanks!

Elaine

Ps, glad the info was useful. I'd like to hear more about the crypt cells.

From: Gibbons, Catherine [mailto:Gibbons.Catherine@epa.gov]
Sent: Tuesday, September 17, 2013 2:49 PM
To: Khan, Elaine@OEHHA
Cc: Painter, Page@OEHHA
Subject: California visit

Hi Elaine!

I've been meaning to write for a while to see if it will still work out to come for a visit on Thursday Sept. 26. I will be staying in Oakland, but I can always come out to Sacramento if that's easier for you both.

Also, Elaine, I have a funny story! Thanks again for sending those papers on de-differentiation and autophagy. I was reading the Chaffer et al. paper and thinking, hmm, this sounds familiar. Then I looked over at my notebook right next to me, which was OPEN to the page of my notes from the AACR meeting here in DC in the spring, and I had written "Gupta, Chaffer, and Weinberg 2009, bidirectional stem cell conversion; initiation by DE-differentiation, post-mitotic cells outside of crypt can migrate to crypt following activation of Wnt; NFkB accelerates crypt transformation." So that's how bad my memory is! Thanks so much for drawing this to my attention again!

Thanks again, and I'll hopefully see you in California!

Catherine

Catherine Gibbons, Ph.D.
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National Center for Environmental Assessment
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Bohn, Brent

From: Gibbons, Catherine
Sent: Friday, December 04, 2015 7:47 PM
To: Bohn, Brent
Subject: FW: Cr6 PBPK Model

From: Khan, Elaine@OEHHA [mailto:Elaine.Khan@oehha.ca.gov]
Sent: Wednesday, February 05, 2014 6:03 PM
To: Gibbons, Catherine <Gibbons.Catherine@epa.gov>; Sasso, Alan <Sasso.Alan@epa.gov>
Subject: RE: Cr6 PBPK Model

Thanks, Catherine! No rush on the meeting – Patty (our PBPK guru-in-training) will be busy wrapping up a project over the next 3 weeks or so. If your schedule looks flexible in March, we can shoot for some time then. Just let me know. Thanks!

Elaine

From: Gibbons, Catherine [mailto:Gibbons.Catherine@epa.gov]
Sent: Wednesday, February 05, 2014 10:22 AM
To: Khan, Elaine@OEHHA; Sasso, Alan
Subject: RE: Cr6 PBPK Model

Hi Elaine!

I was just checking my phone messages and heard your message from a few weeks ago—I've been out of town a lot recently—but I never received a signal that I had a message, I apologize for the delay! But I'm glad you wrote.

Alan and I would be happy to set up a time for a call. I'll discuss possible times/days with Alan and get back to you as quickly as possible.

Thanks so much!

Catherine

From: Khan, Elaine@OEHHA [mailto:Elaine.Khan@oehha.ca.gov]
Sent: Tuesday, February 04, 2014 3:10 PM
To: Sasso, Alan; Gibbons, Catherine
Subject: RE: Cr6 PBPK Model

Hi, Alan.

Yes, Mark was referring to your presentation at SRA in Baltimore. Thank you for sending your talk and abstract to us. I will only share this internally with my staff and executive office as needed (it will not be cited). I look forward to having a discussion with you and Catherine soon.

Elaine

From: Sasso, Alan [mailto:Sasso.Alan@epa.gov]
Sent: Tuesday, February 04, 2014 11:08 AM
To: Khan, Elaine@OEHHA; Gibbons, Catherine
Subject: RE: Cr6 PBPK Model

HI Elaine,

A conference call would be great. When Catherine comes back to the office later this week, we'll be able to schedule one soon.

Mark was probably referring to the talk I gave at the Society for Risk Analysis conference. I have attached that talk, along with the abstract for a poster I plan on presenting at the Society of Toxicology meeting in March.

The material has not yet been peer reviewed, so please do not distribute or cite the materials.

Thanks and take care,

-Alan

Alan F. Sasso, Ph.D.
Office of Research and Development
National Center for Environmental Assessment
U.S. Environmental Protection Agency
(703)-347-0179

From: Khan, Elaine@OEHHA [mailto:Elaine.Khan@oehha.ca.gov]
Sent: Tuesday, February 04, 2014 1:14 PM
To: Gibbons, Catherine; Sasso, Alan
Subject: Cr6 PBPK Model

Hi, Catherine and Alan.

I hope your year has gotten off to a good start so far! I've been keeping in touch with Mark Harris (ToxStrategies) regarding their Cr6 studies and he informed me that they provided you with additional PBPK information, which you used to build your own model. I was wondering if we could set up a conference call sometime soon to touch base on the Cr6 assessment. We're very interested in seeing how your PBPK model differs from theirs. Please let me know when it would be convenient for us to have a meeting. Thanks!

Elaine

Elaine M. Khan, Ph.D., Chief
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Bohn, Brent

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Thanks and take care,

-Alan

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Bohn, Brent

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Sent: Friday, December 04, 2015 7:47 PM
To: Bohn, Brent
Subject: FW: Cr6 PBPK Model

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Sent: Tuesday, February 04, 2014 1:14 PM
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Elaine

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Email: elaine.khan@oehha.ca.gov

Bohn, Brent

From: Gibbons, Catherine
Sent: Friday, December 04, 2015 7:46 PM
To: Bohn, Brent
Subject: FW: Tera Cr(VI) peer reviews

From: Gibbons, Catherine
Sent: Tuesday, March 11, 2014 2:49 PM
To: Khan, Elaine@OEHHA <Elaine.Khan@oehha.ca.gov>
Subject: Tera Cr(VI) peer reviews

http://www.tera.org/Peer/Chromium/Chromium.htm

Bohn, Brent

From: Gibbons, Catherine
Sent: Friday, December 04, 2015 7:46 PM
To: Bohn, Brent
Subject: FW: Cr(VI) raw microarray data

From: Khan, Elaine@OEHHA [mailto:Elaine.Khan@oehha.ca.gov]
Sent: Wednesday, March 12, 2014 3:30 PM
To: Gibbons, Catherine <Gibbons.Catherine@epa.gov>
Subject: RE: Cr(VI) raw microarray data

Good to know. Thank you!

From: Gibbons, Catherine [mailto:Gibbons.Catherine@epa.gov]
Sent: Wednesday, March 12, 2014 12:24 PM
To: Khan, Elaine@OEHHA
Subject: FW: Cr(VI) raw microarray data

FYI!

From: Burgoon, Lyle
Sent: Wednesday, March 12, 2014 9:43 AM
To: cthompson@toxstrategies.com
Cc: tzachare@msu.edu; Gibbons, Catherine
Subject: Cr(VI) raw microarray data

Dr. Thompson,

It was nice seeing you and Dr. Harris (via video) at Monday's meeting @ NCEA HQ. I was quite pleased to hear Ms. Mason state that ACC expected the researchers would share their data and results with NCEA.

I'm following up on our discussion from Monday and am requesting access to all of your raw microarray data, as well as your analyzed data that supports the conclusions in your papers. In addition, it would be helpful if you could also supply us with the analysis code that was used, any protocols used for the analyses, and any other supporting documentation that may help us understand how the assays and analyses were performed.

For clarity, I am using the MIAME definition of "raw data", and my request for the additional information is in line and keeping with the MIAME standard, which can be found here: http://www.mged.org/Workgroups/MIAME/miame.html.

To facilitate data transfer, I can set-up an EPA-based FTP site where you can upload the data.

Thanks again for presenting your latest results to us, and I look forward to receiving the data.

Cheers,

Lyle

Lyle D. Burgoon, Ph.D
National Center for Environmental Assessment
Chief, Hazardous Pollutant Assessment Group (Acting)
US Environmental Protection Agency
Phone: 919.541.7808
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Bohn, Brent

From: Gibbons, Catherine
Sent: Friday, December 04, 2015 7:46 PM
To: Bohn, Brent
Subject: FW: SOT poster
Attachments: Sasso_SOT2014_Cr6-finalv3.pptx

From: Gibbons, Catherine
Sent: Monday, April 14, 2014 4:37 PM
To: Khan, Elaine@OEHHA <Elaine.Khan@oehha.ca.gov>
Cc: Sasso, Alan <Sasso.Alan@epa.gov>
Subject: FW: SOT poster

Hi Elaine!

I am so sorry I never set up a meeting for the first week of April—things have been crazy around here trying to get this first set of Cr(VI) evidence tables ready for release. If you're still interested in having your PBPK person talk with us about our (well, Alan's) modeling efforts, please let me know. I'm attaching Alan's poster from SOT as well.

Also, we still have not tried to access the microarray data that ACC made "available" to the public. There are still many concerns about the legal restrictions placed on simply accessing the data. Has anyone there accessed it?

Thanks, hope you are well!

Catherine

Sensitivity analysis of internal dose-metrics for hexavalent chromium toxicity using physiologically-based pharmacokinetic modeling

Alan F. Sasso, Paul M. Schlosser

U.S. Environmental Protection Agency, National Center for Environmental Assessment

Alan Sasso | sasso.alan@epa.gov | 703-347-0179

www.epa.gov

Abstract

➢Hexavalent chromium (Cr6) is an environmental and occupational contaminant present in soil and drinking water in the United States.

➢The National Toxicology Program found clear evidence of carcinogenic activity in male and female rats and mice in a 2-year drinking water study.

➢Reduction of Cr6 to trivalent chromium (Cr3) is an important detoxifying step in the gastrointestinal (GI) tract. The reduction and absorption of Cr6 is rapid, but varies with intestinal pH, dietary intake, and gastric contents and physiology.

➢Physiologically-based pharmacokinetic (PBPK) models have been developed to estimate internal dose of unreduced Cr6.

➢EPA has adapted these models to improve predictions of Cr6 reduction.

➢This work quantifies the impact of different modeling assumptions on the interpretation of toxicological data in rodents, and extrapolation to humans.

The views expressed are those of the authors, and do not necessarily represent the views or policies of the U.S. EPA.

Hexavalent chromium in the GI tract

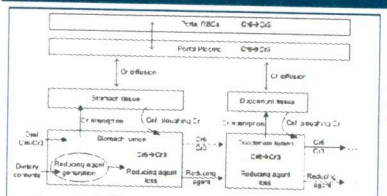

Figure 1. PBPK models can be used to estimate the amount of Cr6 that escapes reduction. Reducing capacity and pH of gastric juice differ between species.

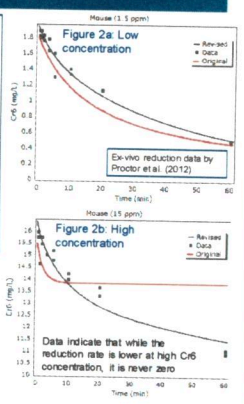

Figure 2 (right). The revised model (black) assumes multiple pathways for reduction. The original model (red) assumes a single pathway (which saturates at high concentration). A multi-pathway model fits the data better, and is more realistic.

U.S. Environmental Protection Agency
Office of Research and Development

Impact of model and internal dose metric

Internal dose metric and PBPK model impact predictions of species differences

Site-specific absorption is the mass of Cr6 that is absorbed in a discrete section of the small intestine (i.e., the duodenum or jejunum), per liter sectional volume.

Pyloric flux is the mass of Cr6 that escapes reduction in the stomach and is emptied into the small intestine (this requires only a physiological model for the stomach).

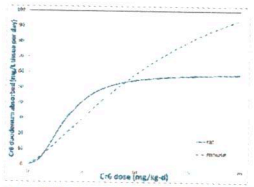

Figure 3. Duodenum absorption (revised model)

The NTP (2008) 2-year oral study indicates mice are more susceptible than rats to small intestinal toxicity and tumors

➢The model does not consistently predict higher site-specific absorption in the mouse over a wide dose range (Fig. 3).

➢Pyloric flux normalized by small intestine (SI) volume predicts rats to have higher internal dose (Fig. 4).

➢If pyloric flux is normalized by body weight (BW), all models indicate higher mouse internal dose (Fig. 5).

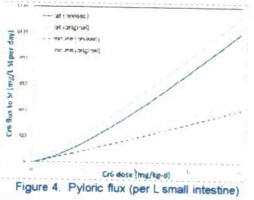

Figure 4. Pyloric flux (per L small intestine)

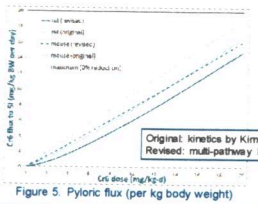

Figure 5. Pyloric flux (per kg body weight)

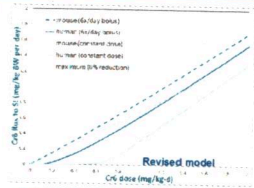

Figure 6. Pyloric flux (per kg body weight)

Oral exposure assumptions impact human internal dose predictions

➢Assuming humans consume chromium in drinking water at a constant rate for 24 hours/day, internal dose is minimized

➢Metabolic saturation↓, Cr6 reduction↑

➢If the daily dose is distributed as 6 bolus events over a 24-hour period (a more realistic assumption), the internal dose increases

➢Metabolic saturation↑, Cr6 reduction↓

Mouse-to-human extrapolation

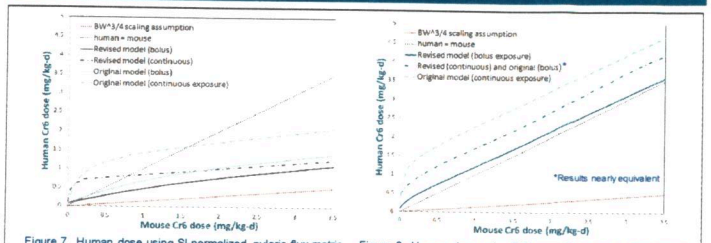

Figure 7. Human dose using SI-normalized pyloric flux metric

Figure 8. Human dose using BW-normalized pyloric flux metric

x-axis: Mouse administered dose. y-axis: Model estimated human administered dose that achieves the same internal dose as in the mouse. Points above the y=x line correspond to oral administered doses that are higher in the human relative to the mouse for an equivalent internal dose.

Conclusions

➢Human internal dose relative to the mouse depends on a number of factors (gastric physiology/pH, ingestion patterns).

➢If pyloric flux is scaled by small intestinal volume, relative species differences vary with model and dose.

➢If pyloric flux is scaled by body weight, results consistently indicate humans have lower internal doses than the mouse.

➢All PBPK-derived human dose extrapolations are significantly higher than the default $BW^{3/4}$ scaling methodology.

Note: These human dose extrapolations are for hypothetical animal exposures being used for illustrative purposes. Doses and body weights used in the modeling are not taken from an actual bioassay.

Acknowledgements and references

We would like to thank Ravi Subramaniam, Catherine Gibbons, Susan Rieth, Gina Perovich, Vincent Cogliano and Lynn Flowers for their helpful comments and review of this poster. We would also like to thank the researchers at Summit Toxicology and ToxStrategies for their sharing of raw pharmacokinetic data and PBPK model codes.

We also acknowledge those who took part in EPA's Cr6 reduction webinar (Elaina Kenyon, Gary Ginsberg, Kim Barrett, Max Costa, John Crison, Silvio DeFlora, and Sean Hays).

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Witt et al. (2013). Mechanistic insights from the NTP Studies of Chromium. *Toxicologic pathology* 41(2), 326-42

Kirman et al. (2012). Physiologically based pharmacokinetic model for rats and mice orally exposed to chromium. *Chemico-biological interactions* 200(1), 45-64

Proctor et al. (2012). Hexavalent chromium reduction kinetics in rodent stomach contents. *Chemosphere 89(5)*, 487-93

Additional references and an overview of Cr6 gut reduction may be obtained from EPA's webinar page: www.epa.gov/iris/irisworkshops/cr6

Bohn, Brent

From: Gibbons, Catherine
Sent: Friday, December 04, 2015 7:45 PM
To: Bohn, Brent
Subject: FW: PBPK Contact

From: Khan, Elaine@OEHHA [mailto:Elaine.Khan@oehha.ca.gov]
Sent: Wednesday, April 16, 2014 6:38 PM
To: Sasso, Alan <Sasso.Alan@epa.gov>
Cc: Wong, Patty@OEHHA <Patty.Wong@oehha.ca.gov>; Gibbons, Catherine <Gibbons.Catherine@epa.gov>
Subject: PBPK Contact

Hi, Alan.
Thanks for providing us with your SOT poster – very interesting! We appreciate that you are willing to share your work with us and we look forward to discussing this further. Our PBPK person is Patty Wong. I've spoken with her and given her a heads up that you will be contacting her. She is on vacation this week and will not be returning to work until Monday, the 21st. You can reach her at:
patty.wong@oehha.ca.gov or (916) 323-2627. Thanks!
Elaine

Bohn, Brent

From: Gibbons, Catherine
Sent: Friday, December 04, 2015 7:45 PM
To: Bohn, Brent
Subject: FW: CDPH Submits Final Regulation Package Regarding Hexavalent Chromium (Cr VI) and Drinking Water
Attachments: removed.txt; PH14-038 CDPH Submits Final Regulation Package Regarding Hexavalent Chromium (Cr VI) and Drinking Water.pdf

From: Khan, Elaine@OEHHA [mailto:Elaine.Khan@oehha.ca.gov]
Sent: Wednesday, April 16, 2014 1:22 PM
To: Gibbons, Catherine <Gibbons.Catherine@epa.gov>
Subject: FW: CDPH Submits Final Regulation Package Regarding Hexavalent Chromium (Cr VI) and Drinking Water

From: Klasing, Susan@OEHHA
Sent: Wednesday, April 16, 2014 8:45 AM
To: Khan, Elaine@OEHHA
Subject: FW: CDPH Submits Final Regulation Package Regarding Hexavalent Chromium (Cr VI) and Drinking Water

FYI

From: CDPHPress (OPA) [mailto:CDPHPressOPA@cdph.ca.gov]
Sent: Tuesday, April 15, 2014 3:46 PM
To: CDPHOPA@MAILLIST.DHS.CA.GOV
Subject: CDPH Submits Final Regulation Package Regarding Hexavalent Chromium (Cr VI) and Drinking Water

News Release

CALIFORNIA DEPARTMENT OF PUBLIC HEALTH

CONTACT: Anita Gore
Heather Bourbeau
(916) 440-7259

FOR IMMEDIATE RELEASE
April 15,
2014
PH14-038

CDPH Submits Final Regulation Package Regarding Hexavalent Chromium (Cr VI) and Drinking Water

SACRAMENTO - The California Department of Public Health (CDPH) today submitted to the Office of Administrative Law (OAL) its final proposed regulation establishing the first ever drinking water Maximum Contaminant Level (MCL) for hexavalent chromium (Cr VI). More than 18,000 comments were received by CDPH regarding the proposed regulation. The proposed final regulation documents include the Summary and Response to comments received.

The proposed final regulation will take effect after it has been reviewed and approved by OAL in compliance with the Administrative Procedures Act. This review can take up to 30 working days to complete. Once approved, the regulation is then filed with the Secretary of State and will become effective the first day of the following quarter.

"The drinking water standard for hexavalent chromium of 10 parts per billion will protect public health while taking into consideration economic and technical feasibility as required by law," said Dr. Ron Chapman, CDPH director and state health officer.

If the regulation is approved as expected, implementation of the new drinking water standard for hexavalent chromium will begin July 1, 2014.

Today's filing also complies with timelines imposed by the Alameda Superior Court in *Natural Resources Defense Council, Inc. v. California Department of Public Health.*

The department's submission to OAL can be found on the CDPH website.

www.cdph.ca.gov

News Release

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